Computers and Electronics in Agriculture 38 (2003) 33–44

Computers and electronics in agriculture

www.elsevier.com/locate/compag

Mapping vineyard leaf area with multispectral satellite imagery

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Received 25 January 2002; received in revised form 2 July 2002; accepted 1 September 2002

Abstract

Vineyard leaf area is a key determinant of grape characteristics and wine quality. As is frequently the case in agriculture, available ground-based leaf area measurements employed by growers are not well suited to larger area mapping. In this study, IKONOS high spatial resolution, multispectral satellite imagery was used to map leaf area throughout two commercial wine grape vineyards (approximately 800 ha) in California's North Coast growing region. The imagery was collected near harvest during the 2000 growing season, converted to at-sensor radiance, geo-referenced and transformed to normalized difference vegetation index (NDVI) on a per pixel basis. Measurements at 24 ground calibration sites were used to convert NDVI maps to leaf area index (LAI; m^2 leaf area m^{-2} ground area); planting density was then used to express leaf area on a per vine basis (LA_v). Image-based LA_v was significantly correlated with ground-based LA_v estimates developed at 23 validation sites ($r^2 = 0.72$; $P < 0.001$). Despite challenges posed by the discontinuous nature of vineyard canopies and architectural differences imposed by shoot positioning trellis systems, remote sensing appears to offer a basis for mapping vineyard leaf area in low LAI vineyards. Such maps can potentially be used to parameterize plant growth models or provide decision support for irrigation and canopy management.
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PII: S0168-1699(02)00106-0

Keywords: Satellite remote sensing; Leaf area; Geospatial technology; Precision viticulture

1. Introduction

Use of airborne imagery has been previously demonstrated for mapping *relative* differences in canopy density within individual vineyard fields (Wildman et al., 1983; Johnson et al., 1998, 2001; Hall et al., 2002). Various wine grape growers in California's Napa Valley and greater North Coast region are using digital, multispectral imagery to monitor vineyard variability for purposes such as harvest preparation, vineyard re-development and identification of problems related to irrigation, nutrient status, disease and pest infestation (Penn, 1999; Carothers, 2000; Aho, 2002). The images are typically collected at 2 m ground sampling distance, geo-referenced and transformed to normalized difference vegetation index (NDVI) per pixel. It has been previously shown that NDVI, calculated as (near-infrared − red)/(near infrared + red), is related to plant canopy leaf area index (LAI; m^2 leaf area m^{-2} ground area) and amount of photosynthetically active radiation absorbed by the canopy (Tucker, 1979; Asrar et al., 1984; Daughtry et al., 1992).

Vineyard leaf area is related to fruit ripening rate (Winkler, 1958), infestation and disease (Wildman et al., 1983; English et al., 1989), water status (Smart and Coombe, 1983), fruit characteristics and wine quality (Smart, 1985; Jackson and Lombard, 1993; Iland et al., 1995). Canopy management methods for leaf area regulation include pruning, shoot thinning, leaf removal, cover crop cultivation, irrigation scheduling and application of soil and crop amendments. Despite its importance, growers have no efficient way of mapping and monitoring leaf area, in *absolute* terms, during the growing season. Direct measurement of leaf area by leaf removal is accurate, yet time-consuming and destructive. Indirect methods include measurement of canopy-intercepted solar radiation, regressions based on shoot length and shoot number, and post-season collection of pruning weights (prior season woody production). While reasonably quick and accurate, these point-based techniques are not designed for mapping applications.

Remote sensing offers a means of greatly increasing sampling density with respect to that achievable by ground-based methods alone. Toward this end, for instance, the relationship between remotely sensed NDVI and leaf area has been explored for many annual crops. Less attention has been paid to this topic in vineyards and other perennial agricultural systems. Vineyard canopies can present some remote sensing challenges. The canopies are highly discontinuous, with foliage clumped in individual vines or along rows, with relatively low overall ground cover fraction. Soils may contain understory foliage as cover crop or weeds, depending on cultivation practice. In addition, canopy architecture can vary among fields due to the use of differing trellis (shoot positioning) systems. Despite factors such as these, recent studies have found strong linear relationships between NDVI and vine development across vineyards in central Spain (Montero et al., 1999; Lanjeri et al., 2001).

The main purpose of this study was to explore the complementary use of high spatial resolution, multispectral satellite imagery and ground measurements for mapping leaf area in California's mild climate vineyards. In doing so, the study sought to implement a whole farm (vs. plot level) research approach as recommended by the National Research Council (1997). A secondary goal was to provide a quantitative indication of the value of commercial IKONOS satellite imagery (Space Imaging, Inc., Thornton, CO) for the extraction of plant canopy biophysical information. This observational system, which first became available during the 2000 growing season, collects multispectral imagery of much finer spatial resolution (4 m ground sampling distance) than previously available from orbit.

2. Methods

2.1. Study areas

Study areas were the Tokalon and Huchica Hills commercial vineyard properties of the Robert Mondavi Winery (Oakville, CA). The 500 ha Tokalon holding is located at approximately 38°25′N/122°25′W in California's mild climate Napa Valley wine grape producing region. Tokalon produces mainly red grape varieties on sandy clay loam soils. The 300 ha Huchica property is located 22 km SE of Tokalon at 38°14′N/122°22′W. Huchica produces white and red varieties on clay soils and hilly terrain. Huchica is situated closer to the San Francisco Bay and has a stronger maritime influence than Tokalon. Both properties are subdivided into many fields that can differ from one another in planting density, trellis structure, biological variety and age. At both areas, maximum LAI is generally attained by late July and persists through harvest in mid- to late-September. As is typical of the region, most of the annual woody production is removed by pruning during dormancy.

2.2. Leaf area calibration

Ground-based calibration sites were established throughout the two study areas to define a relationship between LAI and NDVI. Direct measurements of leaf area were made at 16 sites, and indirect at six sites. Two bare soil sites were established as well, for a total of 24 sites (Table 1). These calibration sites presented variation in trellis system, planting density, biological variety and age. Most sites were cleanly cultivated, with all understory vegetation removed. The remaining sites had dried cover crop grasses and trace amounts of green weeds.

All direct measurement sites employed vertically shoot positioned trellis systems, which is the most common type of canopy architecture currently encountered in the region. Three to six sample vine replicates were measured per site, distributed over an area of approximately 10 m × 10 m. All leaves were removed from each sample vine, placed in separate plastic bags and sealed. Total leaf weight was recorded per sample vine. A subsample was extracted and weighed for each vine. Leaf area of each subsample was measured within 24 h on an electronic meter (Model LI-3000, LI-

Table 1
Calibration sites, sorted by LAI

Study area	Variety	Trellis	Vine spacing (m)	Row spacing (m)	LAI (m^2 m^{-2})
H	Bare soil	n/a	n/a	n/a	0.0
T	Bare soil	n/a	n/a	n/a	0.0
H	CH	V	1.5	2.1	0.4
T[a]	CS	S	1.8	3.7	0.6
T	CS	V	1.2	1.2	0.8
H	CH	V	1.5	2.4	0.8
H[a]	CH	V	1.5	2.4	0.9
T	SG	V	1.5	2.7	1.0
H	CH	V	1.5	2.4	1.0
H	CH	V	1.5	2.4	1.0
T[a]	CF	S	2.4	3.6	1.2
T	CS	V	1.0	1.8	1.4
T	CS	V	1.2	1.2	1.5
T	CS	V	1.2	1.2	1.5
H	CH	V	1.2	1.2	1.5
T[a]	CF	S	1.5	2.8	1.6
H	CH	V	1.5	2.1	1.6
H	CH	V	1.5	2.4	1.6
T	CS	V	1.2	1.2	1.9
H	CH	V	1.2	1.2	2.0
T[a]	CS	Y	1.5	2.7	2.1
T[a]	CS	Y	1.8	3.1	2.2
H	CH	V	1.5	2.4	2.4
T	CS	V	1.0	1.0	2.8

Study area: T, Tokalon; H, Huchica Hills. Variety: CH, chardonnay; CS, cabernet sauvignon; CF, cabernet franc; SG, sangiovese. Trellis type: V, vertical; Y, split; S, sprawl.
[a] Sites of indirect LAI measurement. All others by direct measurement.

COR, Inc., Lincoln, NE). Total leaf area per sample vine was calculated as

$$\mathrm{LA_v} = W_\mathrm{t}\,\mathrm{SLA}, \tag{1}$$

where $\mathrm{LA_v}$ is the leaf area (m^2) per sample vine, W_t the total weight (g) and SLA the specific leaf area (m^2 leaf area g^{-1} fresh weight). Sample vine LAI was then

$$\mathrm{LAI_v} = \frac{\mathrm{LA_v}}{\text{vine area}}, \tag{2}$$

where vine area (m^2) is the product of row and vine spacing. Site LAI was mean $\mathrm{LAI_v}$. All measurements were made shortly after harvest, from 22 September to 6 October 2000.

Indirect measurements of LAI were made at six additional calibration sites based on shoot length observation. Four of these sites were sprawling (untrained) canopies and two used a split (“Y” cross-section) trellis configuration. For each of three sample vines per site, the total number of shoots was counted and mean length (m) calculated from five randomly selected shoots. Mean shoot length was converted to shoot leaf area (LA_{shoot}) by a previously observed relationship

$$LA_{shoot} = -0.036 + 0.301\ (\text{shoot length}), \quad r^2 = 0.64, \ n = 50, \ P < 0.01 \tag{3}$$

(Johnson, unpublished observation on mixed trellis systems), and LA_v was the product of LA_{shoot} (m^2) and the number of shoots on the vine. Eq. (2) was then used to derive LAI_v and, as before, site LAI was set to mean LAI_v.

One bare soil site was established at each study area. These sites were large in comparison with the sensor spatial resolution to assure the extraction of pure pixels, free of vegetation influence. Soil samples were collected, dried, pulverized and passed through a 0.25 mm sieve. Reflectance was then measured with a laboratory spectrophotometer (Fig. 1).

The location of each calibration site was recorded with a Trimble Ag Global Positioning System (GPS) (Trimble, Inc., Sunnyvale, CA). In addition, several control points were taken at conspicuous road intersections to facilitate verification of image alignment. Post-processing, differential correction to nominal submeter accuracy and map projection steps were performed using Trimble Pathfinder Office software.

2.3. Image processing

Two IKONOS 11-bit multispectral satellite images were acquired during the period of full canopy expansion: 21 August 2000, for Huchica Hills (scene No. PO58767) and 4 October 2000, for Tokalon (No. PO53184). The images were collected in the blue (445–526 nm), green (507–595 nm), red (632–698 nm) and near-infrared (757–853 nm) spectral regions under clear sky and dry soil conditions at 11:55 a.m. local time. The Imagine v8.5 software package (ERDAS, Inc., Atlanta, GA) was used for image processing. Digital counts in each spectral channel were converted to at-sensor radiance units by applying radiometric calibration coefficients of Peterson (2001). The images were registered to the California State Plane Coordinate System (Zone II-3301, North American Datum 1983, GRS 80) by image-to-image registration to high-resolution digital orthophotos. The Tokalon image was

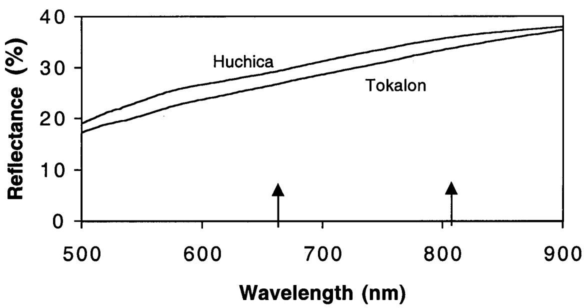

Fig. 1. Soil reflectance at Huchica (top line) and Tokalon (bottom) study sites measured with an NIRS6500 scanning monochromator (Foss NIRSystems, Inc., Silver Spring, MD). Image red and NIR band centers are shown by arrows.

registered to a publicly available 1 m Digital Ortho Quarter Quad (US Geological Survey). To better account for topography, the Huchica Hills image was registered to a custom-acquired, high-accuracy 1:6000 scale orthophoto, generated using survey field control, 5 ft elevation contours and standard photogrammetric methods. The radiance values were then converted to NDVI on a per pixel basis. The individual pixel corresponding to each calibration site was extracted, based on GPS location, and a calibration equation relating NDVI to ground-based LAI was established (Fig. 2). The equation was used to convert each scene from NDVI to LAI on a per pixel basis.

ArcView GIS v3.2 and the Spatial Analyst v2 Extension (both ESRI, Inc., Redlands, CA) were used to convert per-field information on row and vine spacing, contained within the grower's GIS, from vector to raster format. The ArcView GRID processing module was used to derive a vine area raster as the product of the row and vine spacing rasters. GRID was then used to map LA_v at both study areas (Figs. 3 and 4), as the product of LAI and vine area.

2.4. Validation

Post-season pruning weights were recorded for each calibration vine. All shoots produced during the growing season were removed down to the second node and immediately weighed. A significant ($P < 0.001$) calibration relationship between pruning weight and $\ln(LA_v)$ was observed (Fig. 5). These measurements were made during dormancy on 17 November 2000.

Twenty-three validation sites were established: 13 in Huchica and 10 in Tokalon (Table 2). Pruning weights, all within the range of the calibration vines above, were collected on 4–7 vine replications per site. GPS readings were taken for site centers. The measurement period was 15–20 November 2000. The calibration equation of Fig. 5 was used to convert mean pruning weight to mean LA_v per site. These data were then compared with image-based LA_v, based on the extraction of a single pixel per site.

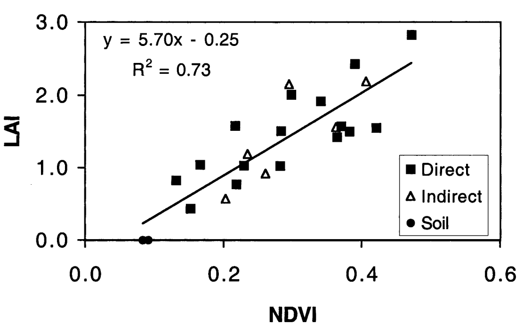

Fig. 2. Image-based NDVI vs. ground-based LAI measurement. Sites of direct and indirect LAI measurement as indicated. Points with zero LAI represent bare soil at each study area.

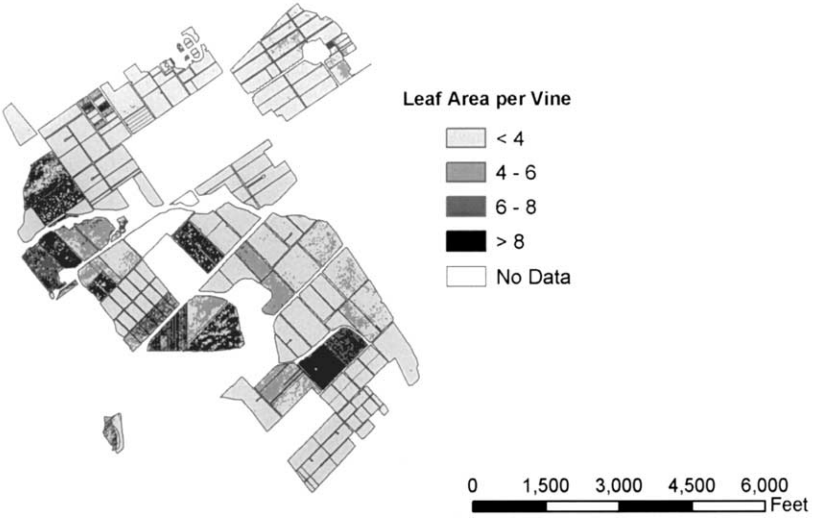

Fig. 3. Image-based map of LA_v (m^2) at Tokalon study area arbitrarily grouped into four discrete levels.

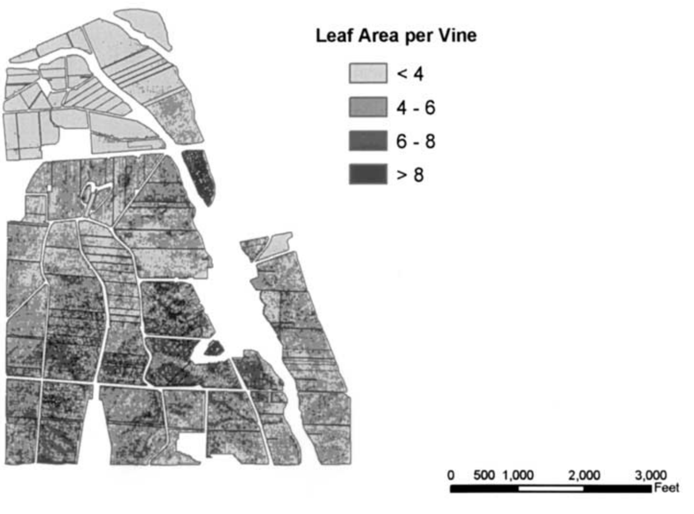

Fig. 4. Image-based map of LA_v (m^2) at Huchica study area arbitrarily grouped into four discrete levels.

3. Results and discussion

Ground-based LAI measurements ranged from 0.4 to 2.8 at the vegetated calibration sites. This range is fairly typical of the California's mild climate, coastal vineyard regions. Bare soil was brighter in NIR than in the red (Fig. 1) and hence yielded a mildly positive NDVI at both study areas: 0.08 at Tokalon and 0.09 at Huchica.

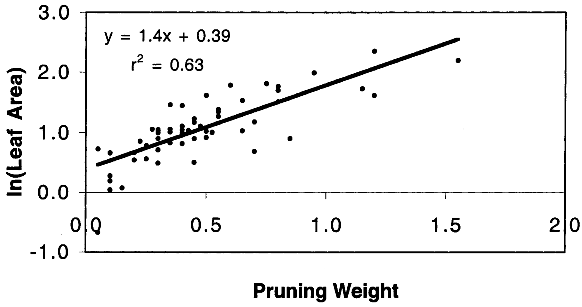

Fig. 5. Relationship between pruning weight (kg) and natural logarithm of LA_v (m^2) for 59 calibration site vines.

Table 2
Validation sites, sorted by pruning weight

Variety	Trellis	Vine space (m)	Row space (m)	Pruning weight (kg)	LA_v (ground) (m^2)	LA_v (image) (m^2)
CH	V	1.2	1.2	0.11	1.4	2.0
PN	V	1.2	1.2	0.11	1.4	1.8
CS	V	1.2	1.2	0.28	2.3	3.1
ZN	V	1.5	1.8	0.30	2.4	4.0
ME	V	1.5	2.4	0.31	2.5	4.3
PN	V	1.5	2.4	0.32	2.5	3.0
CH	V	1.2	1.2	0.35	2.6	3.2
ME	V	1.5	2.4	0.56	3.7	5.6
CF	S	1.5	2.7	0.59	3.9	6.5
ME	V	1.5	2.1	0.65	4.2	4.1
CH	V	1.5	2.4	0.67	4.3	5.1
CS	S	1.8	3.7	0.68	4.3	5.4
CS	S	2.4	3.0	0.75	4.7	6.5
CH	V	1.5	2.4	0.82	5.1	5.8
CF	S	1.5	2.7	0.84	5.2	7.9
CF	S	2.4	3.7	1.02	6.1	8.8
ME	V	1.5	2.4	1.11	6.5	5.7
CH	V	1.5	2.4	1.20	7.0	8.4
ME	V	1.5	2.4	1.27	7.4	6.4
CS	V	1.5	2.4	1.32	7.6	5.8
CF	S	2.4	3.7	1.33	7.7	9.7
CS	S	2.4	3.0	1.43	8.2	11.7
CS	V	3.0	1.8	1.52	8.7	7.7

Variety: CH, chardonnay; PN, pinot noir; CS, cabernet sauvignon; ZN, zinfandel; ME, merlot; CF, cabernet franc; SB, sauvignon blanc. Trellis type: V, vertical; S, sprawl. All leaf areas (LA) are in m^2.

A significant linear NDVI–LAI calibration relationship was observed as

$$\mathrm{LAI} = 5.7\mathrm{NDVI} - 0.25, \quad r^2 = 0.73, \quad n = 24, \quad P < 0.001 \tag{4}$$

(Fig. 2). The finding of linearity is consistent with that of Montero et al. (1999), who found such a relationship in vineyards with LAI ranging up to approximately 3.4. The tendency for NDVI to begin to saturate at LAI > 2, as observed in other crops such as wheat and corn (Asrar et al., 1984; Bausch and Neale, 1987), was not evident in these data. There is ample empirical and theoretical evidence (Myneni et al., 1997) suggesting that NDVI saturation would occur in higher LAI, unpruned or minimally pruned vineyards.

Ground- and image-based estimates of $\ln(LA_v)$ were significantly correlated ($r^2 = 0.72$, $P < 0.001$) at the validation sites (Fig. 6). However, the slope of the relationship (0.67) was significantly different from 1. This is to be expected due to the presence of errors in the independent (ground) data. With respect to the case at hand, it can be shown (after Kendall and Stuart, 1979) that the expected slope is

$$\beta_{\text{exp}} = \frac{1}{1 + \sigma_\delta^2/(\sigma_\xi^2 - \sigma_\delta^2)}, \tag{5}$$

where σ_δ is the standard deviation of the calibration residuals (Fig. 5) and σ_ξ the standard deviation of ground data (Fig. 6) as predicted from pruning weights. Substituting observed values of 0.326 for σ_δ and 0.616 for σ_ξ yielded β_{exp} of 0.71. The observed slope was not significantly different from β_{exp}.

NDVI was used in this study because it is straightforward to implement, is commonly used and has achieved a certain level of acceptance in the North Coast wine industry for relative vigor mapping. The index is known to be sensitive to differences in soil brightness (Huete et al., 1985) and atmospheric turbidity (Slater and Jackson, 1982). As well, NDVI can be influenced by foliage distribution, or clumping, of the canopy (Myneni and Williams, 1994). The calibration and validation sites used in this study varied with respect to foliage distribution, and had mild to moderate (2–3% absolute) differences in red and NIR soil reflectance. Atmospheric turbidity was not measured during the image collection periods. Given the temporal (6 weeks) and spatial (22 km) differences between image acquisitions, differences in atmospheric conditions can be assumed. Heterogeneity in these factors enables the study results, at least to first approximation, to be viewed in the context of wider area, operational monitoring.

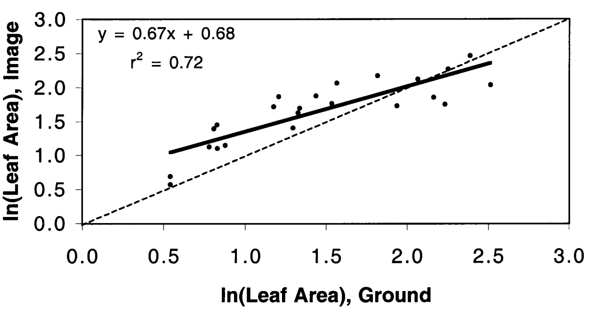

Fig. 6. Ground-based vs. image-based LA_v (m^2) for 23 validation sites. Both variables transformed to natural logarithm. Dashed 1:1 line shown for reference.

A number of additional vegetation index transforms have been developed to reduce uncertainties related to the above confusion factors. These transforms include the soil adjusted vegetation index (Huete, 1988), atmospherically resistant vegetation index (Kaufman and Tanre, 1992) and several others (Schowengerdt, 1997). As a practical matter, selection of a specific transform should consider performance in the research setting as well as computational burden or ancillary data requirement that might affect feasibility of operational implementation.

4. Conclusions

Benefits of vineyard canopy management include improved wine quality, improved yield, reduced disease incidence and facilitation of mechanized operations (Smart and Robinson, 1991). Remote sensing can potentially serve as a decision support tool in this regard by providing quantitative maps of leaf area. Value could be added to such a product in combination with yield data to map vine ‘‘balance’’ (leaf area to crop mass ratio).

Satellite image data used in this study were combined with ground measurements to derive and map LA_v in mild climate wine grape vineyards. Image spatial resolution was sufficient to detect canopy variability at the subfield level. A significant relationship was observed between ground-based and image-based LA_v at 23 validation sites, however, with some bias in regression slope. The study results primarily apply to relatively low LAI (< 3) vineyards planted on varying trellis type. Further investigation might address the effectiveness of remote sensing for quantitative mapping in higher LAI vineyards, and vegetation index optimization.

Acknowledgements

The study was sponsored by NASA’s Office of Earth Science (No. NAG13-99020) and NASA’s Scientific Data Purchase Program (No. NAS13-98048). We gratefully acknowledge the technical support of J. DeMartino, D. Monroe and L. Tolbert. V. Vanderbilt of NASA Ames Research Center assisted in planning and conducting direct measurements of leaf area. C. Hlavka of NASA Ames Research Center assisted with statistical methodology. Use of trade names is for informational use only.

References

Aho, J.E., 2002. NASA providing new perspectives on vineyard management. Vineyard Winery Manage, vol. 28, no. 4, pp. 74–77.

Asrar, G., Fuchs, M., Kanemasu, E.T., Hatfield, J.L., 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. Agron. J. 76, 300–306.

Bausch, W.C., Neale, C.M.U., 1987. Crop coefficients derived from reflected canopy radiation: a concept. Trans. Am. Soc. Agric. Eng. 30, 703–709.

Carothers, J., 2000. Imagery technology meets vineyard management. Pract. Winery Vineyard, vol. 21, no. 1, pp. 54–62.
Daughtry, C.S.T., Gallo, K.P., Goward, S.N., Prince, S.D., Kustas, W.P., 1992. Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies. Remote Sens. Environ. 39, 141–152.
English, J.T., Thomas, C.S., Marois, J.J., Gubler, W.D., 1989. Microclimates of grapevine canopies associated with leaf removal and control of Botrytis bunch rot. Phytopathology 79, 395–401.
Hall, A., Lamb, D.W., Holzapfel, B., Louis, J., 2002. Optical remote sensing applications in viticulture: a review. Aust. J. Grape Wine Res. 8, 36–47.
Huete, A.R., 1988. A soil-adjusted vegetation index (SAVI). Remote Sens. Environ. 25, 295–309.
Huete, A.R., Jackson, R.D., Post, D.F., 1985. Spectral response of a plant canopy with different soil backgrounds. Remote Sens. Environ. 17, 37–53.
Iland, P.G., Botting, D.G., Dry, P.R., Giddings, J., Gawel, R., 1995. Grapevine canopy performance. In: Proceedings of the Canopy Management Viticulture Seminar. Australian Society of Viticulture and Oenology, Inc, Glen Osmond, SA, pp. 18–22.
Jackson, D.I., Lombard, P.B., 1993. Environmental and management practices affecting grape composition and wine quality: a review. Am. J. Enol. Viticulture 44, 409–430.
Johnson, L.F., Lobitz, B.M., Bosch, D.F., Williams, D.F., Wiechers, S., Skinner, P., 1998. Of pixels and palates: can geospatial technology help produce a better wine? In: Proceedings of the First International Conference on Geospatial Information in Agriculture and Forestry, vol. 2. ERIM International, Inc, Ann Arbor, MI, pp. 469–476.
Johnson, L.F., Bosch, D.F., Williams, D.C., Lobitz, B.M., 2001. Remote sensing of vineyard management zones: implications for wine quality. Appl. Eng. Agric. 17, 557–560.
Kaufman, Y.J., Tanre, D., 1992. Atmospherically resistant vegetation index (ARVI) for EOS-MODIS. IEEE Trans. Geosci. Remote Sens. 30, 261–270.
Kendall, M., Stuart, A., 1979. The Advanced Theory of Statistics. Volume 2: Inference and Relationship, 4th ed.(Section 29.56). Charles Griffin & Company Limited, London.
Lanjeri, S., Melia, J., Segarra, D., 2001. A multitemporal masking classification method for vineyard monitoring in central Spain. Int. J. Remote Sens. 22, 3167–3186.
Montero, F.J., Melia, J., Brasa, A., Segarra, D., Cuesta, A., Lanjeri, S., 1999. Assessment of vine development according to available water resources by using remote sensing in La Mancha, Spain. Agric. Wat. Manage. 40, 363–375.
Myneni, R.B., Williams, D.L., 1994. On the relationship between FAPAR and NDVI. Remote Sens. Environ. 49, 200–211.
Myneni, R.B., Nemani, R.R., Running, S.W., 1997. Estimation of global leaf area index and absorbed PAR using radiative transfer models. IEEE Trans. Geosci. Remote Sens. 35, 1380–1392.
National Research Council, 1997. Precision Agriculture in the 21st Century. National Academy Press, Washington, DC.
Penn, C., 1999. Grape growers gravitating toward space age technologies. Wine Business Mon. 6 (2), 53–56.
Peterson, B., 2001. IKONOS relative spectral response and radiometric calibration coefficients. Document Number SE-REF-016, Rev. A. Space Imaging, Inc., Thornton, CO.
Schowengerdt, R.A., 1997. Remote Sensing, Models and Methods for Image Processing. Academic Press, San Diego, CA.
Slater, P.N., Jackson, R.D., 1982. Atmospheric effects on radiation reflected from soil and vegetation by orbital sensors using various scanning directions. Appl. Opt. 21, 3923–3931.
Smart, R.E., 1985. Principles of grapevine canopy microclimate manipulation with implications for yield and quality. Am. J. Enol. Viticulture 36, 230–239.
Smart, R.E., Coombe, B.G., 1983. Water relations of grapevines. In: Kozlowski, T. (Ed.), Water Deficits and Plant Growth, vol. 2. Academic Press, New York, pp. 137–196.
Smart, R.E., Robinson, M., 1991. Sunlight into Wine. Winetitles, Underdale, SA.
Tucker, C.J., 1979. Red and photographic infrared linear combinations for monitoring vegetation. Remote Sens. Environ. 8, 127–150.

Wildman, W., Nagaoka, R., Lider, L., 1983. Monitoring spread of grape phylloxera by color infrared aerial photography and ground investigation. Am. J. Enol. Viticulture 34, 83–94.

Winkler, A.J., 1958. The relation of leaf area and climate to vine performance and grape quality. Am. J. Enol. Viticulture 9, 10–23.